Decaying Neutrinos and the Flattening of the Galactic Halo

D.W. Sciama

S.I.S.S.A., I.C.T.P., Strada Costiera 11, 34014 Trieste, Italy
Nuclear and Astrophysics Laboratory, University of Oxford
e-mail: sciama@sissa.it

ABSTRACT The recently constructed Dehnen-Binney set of mass models for the Galaxy is used to show that the decaying neutrino theory for the ionisation of the interstellar medium (Sciama 1990a, 1993) requires the neutrino halo of the Galaxy to be as flattened as is observationally permitted (axial ratio $q = 0.2$ or shape E8). The argument involves an evaluation of the contribution of red-shifted decay photons from the cosmological distribution of neutrinos to the extragalactic diffuse background at $1500\mathring{A}$. This contribution must be as large as is observationally permitted. These two requirements depend on the decay lifetime τ in potentially conflicting ways. For consistency to be achieved τ must lie within 30 per cent of 10^{23} seconds.

1   Introduction

It gives me great pleasure to dedicate this paper to Engelbert Schucking, whose subtle mind has illuminated many problems in cosmology and general relativity. I hope that he enjoys the way in which, because of the pervasiveness of neutrinos, cosmology and galactic astronomy become interdependent in the decaying neutrino theory for the ionisation of the interstellar medium (Sciama 1990a, 1993). I shall give an example of this interdependence here. My discussion also exemplifies two other useful features of the decaying neutrino theory. Firstly the theory leads to specific and testable predictions concerning the configuration of various matter distributions. For example, it predicts that, if the ionisation of hydrogen in an opaque region of the Galaxy is mainly due to decay photons, then the resulting electron density will be independent of the neutral hydrogen density in the region. There is observational evidence in support of this prediction (Sciama 1990b, 1997). The second feature is that various observations have reduced the domain of validity of the theory to a small region of its parameter space. For example, the energy E_γ of a decay photon in the rest frame of the decaying neutrino is constrained with a precision of one per cent ($E_\gamma = 13.7 \pm 0.1 \ eV$). While this feature may eventually lead to the demise of the theory, it has so far managed to survive.

In this paper I provide another example of these two features, which is based on a new set of comprehensive mass models of the Galaxy (Dehnen and Binney 1997). I will demonstrate that, if the decaying neutrino theory is correct, the neutrino halo of our Galaxy must be flattened to the maximum extent allowed by these models, that is, with an axial ratio $q = 0.2$, corresponding to a shape factor E8 (where q is related to En by $q = 1 - n/10$). Associated with this result is a constraint imposed on the neutrino decay lifetime τ, whose value is required to be close to 10^{23} seconds. The argument leading to these conclusions is based on the following observational results in addition to those underlying the Dehnen-Binney models:

(i) Pulsar dispersion data imply that the free election density in the intercloud medium within one kiloparsec of the sun lies in the range $0.04 - 0.06$ cm^{-3} (Reynolds 1990, Sciama 1990b) and these free electrons have a scale height ∼1 kpc (Reynolds 1991, Nordgren et al 1992, Taylor and Cordes 1993).

(ii) Hα data imply that there are 4x10^6 hydrogen ionisations per cm^2 per sec along a column at the sun perpendicular to the galactic plane (Reynolds 1984).

(iii) The isotropic extragalatic photon flux at $1500\mathring{A}$∼300 ± 80 photons cm^{-2} sec^{-1} ster^{-1} $\mathring{A}^{-1}$ (continuum units or CU) (Henry and Murthy 1993, Witt and Petersohn 1994). This value is still somewhat controversial (compare Bowyer 1991 with Henry 1991). In fact a significantly smaller value would rule out the decaying neutrino theory, as we shall see.

2   The Neutrino Density near the Sun

The neutrino density $n_\nu(0)$ near the sun, which we are assuming to be mainly responsible for the free electron density n_e in opaque regions of the intercloud medium, will be given in ionisation equilibrium by

$$\frac{n_\nu(0)}{\tau} = \alpha n_e^2 \ ,$$

where α is the hydrogen recombination coefficient excluding transitions directly to the ground state. There is, however, a danger that the decaying neutrino theory may lead to a value for $n_\nu(0)$ which is larger than is permitted by the Dehnen-Binney mass models. We therefore immediately adopt the smallest observationally allowed values for α and n_e, namely 2.6x10^{-13}cm^{3}sec^{-1} (corresponding to the reasonable electron temperature of 10^4 K (Osterbrock 1989)) and 0.04 cm $^{-3}$ respectively. Then

$$n_\nu(0) = 4.16\text{x}10^7 \tau_{23} \text{ cm}^{-3} \ ,$$

where $\tau = 10^{23} \tau_{23}$ secs. We may convert this number density of neutrinos into a mass density $\rho_\nu(0)$ by using the mass derived for a decaying neutrino in the theory, namely 27.4 ± 0.2 eV (Sciama 1993). We then find that

$$\rho_\nu(0) = 2.04\text{x}10^{-24} \ \tau_{23} \ \text{gm.cm}^{-3}$$

$$= 0.03 \ \tau_{23} \ \text{M}_\odot \ \text{pc}^{-3} \ .$$

We now ask what is the largest observationally permitted value for $\rho_\nu(0)$, since we shall soon see that the extragalactic background at $1500\mathring{A}$ leads to a strong lower bound on τ_{23}. The mass models of Dehnen and Binney (1997) provide a detailed answer to this question (cf. also Gates et al 1995), but a rough estimate can be derived in the following simple manner. We may obtain observational constraints on $\rho_\nu(0)$ in two ways, by considering (i) estimates for the total density $\rho(0)$ near the sun (the Oort limit) and (ii) the column densities at the sun for various matter distributions. The value of the Oort limit is controversial (eg Kuijken and Gilmore (1991), Bahcall et al 1992). Recent data from the Hubble Space Telescope have placed strict limits on the contribution to $\rho(0)$ from very faint stars (eg. Gould et al 1996). A reasonable upper limit on $\rho_\nu(0)$, derived from observational estimates of the gravitational force due to $\rho(0)$within$\sim$300 pcs of the plane and of the density $\rho_{obs}(0)$ of observed material, would be 0.1 $\text{M}_\odot$ pc^{-3}, which would lead to an upper limit on τ_{23} of$\sim$3. In this connexion we note that Binney et al suggested already in 1987 that all the dark matter near the sun might be due to a flattened halo.

A more stringent upper limit on $\rho_\nu(0)$, and therefore on τ_{23}, follows from considering various column densities at the sun. According to Kuijken and Gilmore (1991) the column density $\sum_{1.1}$ of the observed and dark matter combined out to 1.1 kpc is 71 ± 6 $\text{M}_\odot$ pc^{-2}. Some authors have argued that their error estimates should be increased somewhat (eg. Bahcall et al 1994). We therefore follow Gates et al (1995) and assume that $\sum_{1.1} \leq 100$ $\text{M}_\odot$ pc^{-2}. For the total column density $\sum_{obs}$ of the observed material at the sun we adopt $\sum_{obs} = 40\text{M}_\odot$ pc^{-2} (Gould et al 1996). Hence $\sum_{\nu,1.1} \leq$ $60\text{M}_\odot$ pc^{-2}. So long as the scale height of the neutrino distribution is much greater than 1.1 kpc, we have that 0.03 τ_{23} x2.2x$10^3 \leq$ 60 and so $\tau_{23} \leq$ 0.9. In view of the uncertainties in the values we have adopted we shall suppose that $\tau_{23} \leq$ 1. Thus the upper limit on $\rho_\nu(0)$ is 0.03 $\text{M}_\odot$ pc^{-3}. When we come to consider the background at $1500\mathring{A}$ we shall find that $\tau_{23} \geq 1$, so that the only consistent possibility is $\tau_{23} \sim 1$ and $\rho_\nu(0) \sim 0.03$ $\text{M}_\odot\text{pc}^{-3}$. We therefore examine the implications of this value of $\rho_\nu(0)$ for the flattening of the neutrino halo.

Since a large $\rho_\nu(0)$ implies a flattened neutrino halo, we begin by considering the total column density $\sum_{rot}$ of a flattened system required to account for the rotation velocity v_c of the Galaxy at the sun's position

$(R = R_\odot)$. Binney and Tremaine (1987) give for this quantity

$$\sum_{rot} = \frac{v_c^2}{2\pi G R_\odot}$$
$$= 210 \text{ M}_\odot \text{ pc}^{-2}$$

for $v_c = 220$ km sec^{-1} and $R_\odot = 8.5$ kpc. Hence

$$\sum_\nu = 170 \text{ M}_\odot \text{ pc}^{-2} \, ,$$

and so the scale height l_ν of the neutrino distribution is given by $l_\nu = 2.8$ kpc, which is indeed substantially greater than 1.1 kpc, so that our previous discussion is valid. To derive the implied flattening of the neutrino halo we assume that the neutrino distribution in the plane has the form $\rho_\nu(r) = \rho_\nu(0)a^2/(a^2 + r^2)$, with $a = 8$ kpc (Sciama 1993).Then the "scale-height" in the plane is $\pi a/2$ or 4π kpc, and so the flattening q is given by $q = 0.2$, corresponding to the shape $E8$. This simple reasoning is confirmed by the Dehnen-Binney models which Walter Dehnen kindly extended for me to include $q = 0.3$ and $q = 0.2$, for which $\rho_\nu(0) = 0.03$M$_\odot$ pc^{-3} lies just on the edge of the allowed range of models (cf. also Gates et al. 1995).

3 τ_{23} and the $H\alpha$ Data

We now show that Reynolds' (1984) $H\alpha$ data, as interpreted by the decaying neutrino theory, also lead to the result $\tau_{23} \sim 1$. We consider separately the ionisations produced by decay photons in the opaque layer of free electrons lying above and below the sun out to a distance l and those produced by decaying neutrinos lying in the transparent regions outside this layer. A detailed model of the opaque layer would be complicated, because we should consider the contribution of both clouds and the intercloud medium to the opacity. For simplicity we shall assume that the opaque region corresponds to the electron layer of scale height l as derived from the pulsar dispersion data. Reynolds (1991), Nordgren et al (1992) and Taylor and Cordes (1993) found that $l \sim 1$ kpc. Inside this opaque layer every decay photon produces an ionisation in its vicinity, so along a line of sight normal to the galactic plane there will be n_l ionisations in this layer, where $n_l = 2.6$x10^{-13}x$(0.04)^2$x6x10^{21} or 2.5x10^6. The column density of neutrinos outside the opaque layer corresponds to 115.5 M$_\odot$ pc^{-2} and so is 5x10^{29} neutrinos cm^{-2}. The number of ionisations which they produce inside the layer is reduced by the usual factor 4 which arises from an integration over solid angle related to the slab geometry. Hence they produce 5x$10^6/(4\,\tau_{23})$ ionisations cm^{-2}sec^{-1}. Thus

$$\frac{1.25\text{x}10^6}{\tau_{23}} + 2.5\text{x}10^6 = 4\text{x}10^6 \, ,$$

or

$$\tau_{23} = 0.8 \ .$$

Given the simplicity of our model for the opaque layer we round this result off to $\tau_{23} \sim 1$, which is just compatible with our previous result $\tau_{23} \leq 1$.

4 τ_{23} and the Extragalactic Background at $1500\mathring{A}$

Some of the earliest lower limits on τ_{23} were based on observational esti-mates of the cosmic background in the far u-v, due to red-shifted decay photons produced by the cosmological distribution of neutrinos (Stecker 1980, Kimble et al 1981). As mentioned in the introduction we here adopt an observed flux of 300 ± 80CU at $1500\mathring{A}$. The most recent estimate (Ar-mand et al 1994) for the contribution due to galaxies at $2000 \ \mathring{A}$ is $40 - 130$ CU. The red-shifted contribution from decay photons has recently been recalculated by Sciama (1991), Overduin et al (1993) and Dodelson and Jubas (1994). The main uncertainty arises from absorption by dust in the Galaxy. Allowing a factor 2 for this absorption, one obtains $400 \ \tau_{23}^{-1}$ CU. Given the uncertainties, a reasonable conclusion is that

$$\tau_{23} \geq 1.$$

In conjunction with our previous discussion we arrive at a solution which is just consistent with all the observational constraints, with

$$\tau_{23} \sim 1 \ ,$$

$$\rho_\nu(0) \sim 0.03 \ \mathrm{M}_\odot \ \mathrm{pc}^{-3},$$

$$q \sim 0.2 \ .$$

This solution corresponds to the most flattened possible halo for our Galaxy (E8).

5   Conclusions

We ask in conclusion whether such a large flattening is otherwise reason-able. I believe that it is. It is noteworthy that another galaxy, NGC4650A, is observed to have a highly flattened halo. This was deduced from obser-vations of an outer ring of gas, dust and stars which are on orbits that are nearly perpendicular to the plane of the flattened central galaxy, which ro-tates about its own apparent minor axis (a polar ring galaxy) These orbits delineate the gravitational potential of the galaxy outside its central plane. Sackett et al (1994) deduced that the halo of this galaxy is flattened to-wards the plane of its central body. They state that whenever the data were

ambiguous they attempted to err on the side of favouring rounder halos. Still they found for this galaxy that q lies between 0.3 and $0.4(E6 - E7)$. I therefore regard the requirement from the decaying neutrino theory, that the dark halo of our Galaxy is as flat as it could possibly be, is a reasonable one.

6   Acknowledgements

7   References

[1] C. Armand, B. Milliard and J.M. Deharveng, *Astron. and Astrophys.* **284** (1994) 12.

[2] J.N. Bahcall, C. Flynn and A.Gould, *Ap.J.* **389** (1992) 234.

[3] J.N. Bahcall, C. Flynn, A.Gould and S. Kirhakos, *Ap.J.* **435** (1994) L 51.

[4] J.J. Binney, A. May and J.P. Ostriker, *MNRAS* **226** (1987) 149.

[5] J.J. Binney and S. Tremaine, *Galactic Dynamics*, Princeton University Press (1987).

[6] S. Bowyer, *Ann.Rev.Astr.Ap.* **29** (1991) 59.

[7] W. Dehnen and J.J. Binney, *MNRAS* in press (1997).

[8] S. Dodelson and J.M. Jubas, *MNRAS* **266** (1994) 886.

[9] E.I. Gates, G. Gyuk and M.S. Turner, *Ap.J.* **449** (1995) L123.

[10] A. Gould, J.N. Bahcall and C. Flynn, *Ap.J.* **465** (1996) 759.

[11] R.C. Henry, *Ann.Rev.Astr.Ap.* **29** (1991) 89.

[12] R.C. Henry and J. Murthy, *Ap.J.* **418** (1993) L17.

[13] R. Kimble, S. Bowyer and P. Jakobsen, *Phys.Rev.Lett.* **46** (1981) 80.

[14] K. Kuijken and G.Gilmore, *Ap.J.* **367** (1991) L9.

[15] T. Nordgren, J. Cordes and Y. Terzian, *A.J.* **104** (1992) 465.

[16] D.E. Osterbrock *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, University Science Books, Mill Valley CA (1989).

[17] J.M.Overduin, P.S. Wesson and S. Bowyer, *Ap.J.* **404** (1993) 1.

[18] R.J. Reynolds, *Ap.J.* **282** (1984) 191.

[19] R.J. Reynolds, *Ap.J.* **348** (1990) 153.

[20] R.J. Reynolds, in *IAU Symposium No.144 The Interstellar Disk-Halo Connection in Galaxies*, ed. H. Bloemen, Kluwer, Dordrecht (1991) p. 67.

[21] P.D. Sackett, H-W. Rix, B.J. Jarvis and K.C. Freeman, *Ap.J.* **436** (1994) 629.

[22] D.W. Sciama, *Ap.J.* **364** (1990a) 549.

[23] D.W. Sciama, *Nature* **346** (1990b) 40.

[24] D.W. Sciama, in *The Early Observable Universe from Diffuse Backgrounds*, ed. G. Rocca-Volmerange, J.M. Deharveng and J. Tran Thanh Van, Edition Frontieres (1991) p. 127.

[25] D.W. Sciama, *Modern Cosmology and the Dark Matter Problem* Cambridge University Press (1993).

[26] D.W. Sciama, *Astro-ph* **9702188** (1997).

[27] F.W. Stecker, *Phys.Rev.Lett.* **45** (1980) 1460.

[28] J.H. Taylor and J.M. Cordes, *Ap.J.* **411** (1993) 674.

[29] A.N. Witt and J.K. Petersohn, in the *First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds* ASP Conf. Series Vol.58, ed R.M. Cutri and W.B. Latter (1994).